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A Generalized Propulsor/Turbomachinery Description Standard: Introduction and User's Manual

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PREFACE

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13. ABSTRACT *(Maximum 200 words)*

This is a brief introduction to the formulation of a generalized propulsor/turbomachinery description standard and a guide for its usage. This turbomachinery descriptor is a generalization to arbitrary axisymmetric stream surfaces of both the cylindrical- and conical-based descriptions currently in use. User's manuals are given for both the generation of blade surface coordinates from the generalized blade description parameters (program PRPGEOM) and for the inverse problem of the determination of the blade description parameters from existing blade surface coordinates (program PRMEXT).

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LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

ϕ	Pitch angle of nose/tail pitch helix on cylindrical stream surfaces
ϕ_m	Midchord pitch angle of nose/tail pitch geodesic on axisymmetric stream surfaces
x_m	Rake of the midchord point of the nose/tail pitch line on cylindrical stream surfaces
s_m	Rake of the midchord point of the nose/tail pitch line on axisymmetric stream surfaces
θ_m	Skew of the midchord point of the nose/tail pitch line on axisymmetric stream surfaces
c	Chord length along the nose/tail pitch line
f_{max}	Maximum blade section camber
t_{max}	Maximum blade section thickness

A GENERALIZED PROPULSOR/TURBOMACHINERY DESCRIPTION STANDARD: INTRODUCTION AND USER'S MANUAL

INTRODUCTION

The current propulsor description standard defines the blade sections on cylindrical surfaces whose axes are coincident with the axis of rotation of the propulsor. For propulsor designs in which the inflow is essentially cylindrical, this description conveniently expresses the blade parameters (pitch, chord, rake, skew, camber, and thickness) along blade sections lying on stream surfaces. This fact allows for ready interpretation of the significance of the blade description parameters and easy visualization of the blade shape. However, for propulsor designs for which the inflow stream surfaces are not well approximated by cylinders, these advantages are lost. The description based on cylindrical stream surfaces may still be employed to define the blade shape, but dummy sections must be defined in the way of the hub and the tip to account for the non-cylindrical nature of the stream surfaces there.

To address these problems, the cylindrical stream surface description has been extended by some (reference 1) to assume conical stream surfaces. Conical stream surfaces conveniently include cylindrical stream surfaces as a special case but are still quite restrictive. On reflection, it becomes apparent that to describe the greatest variety of turbomachinery with a single standard, it is necessary to allow for arbitrary axisymmetric stream surfaces.

Employing arbitrary stream surfaces for the description of the blade sections has the following benefits:

- It allows the blade section descriptions to truly represent the blade section seen by the flow during its passage through the propulsor, allowing for easy interpretation of the significance of the blade section description parameters;

- It allows the blade hub and tip sections to be immediately fit to their respective boundaries, simplifying certain manufacturing processes and allowing any filleting to be incorporated into the blade geometry description directly; and

- It allows a wide variety of turbomachinery, including axial-flow, mixed-flow, and radial-flow turbomachinery to be described using a single standard (examples of this flexibility are presented in figure 1).

BLADE DESCRIPTION STANDARD

This document is a brief introduction to a new, generalized turbomachinery description standard and its mathematical basis. It represents a first attempt at providing such a generalized blade description standard. The standard allows for arbitrary axisymmetric stream surfaces on which the blade sections may be defined and employs a number of differential geometric concepts in its determination of the blade section coordinates. Programs are given for both the generation of blade surface coordinates from the generalized blade description parameters (program PRPGEOM) and for the inverse problem of the determination of the blade description parameters from existing blade surface coordinates (program PRMEXT).

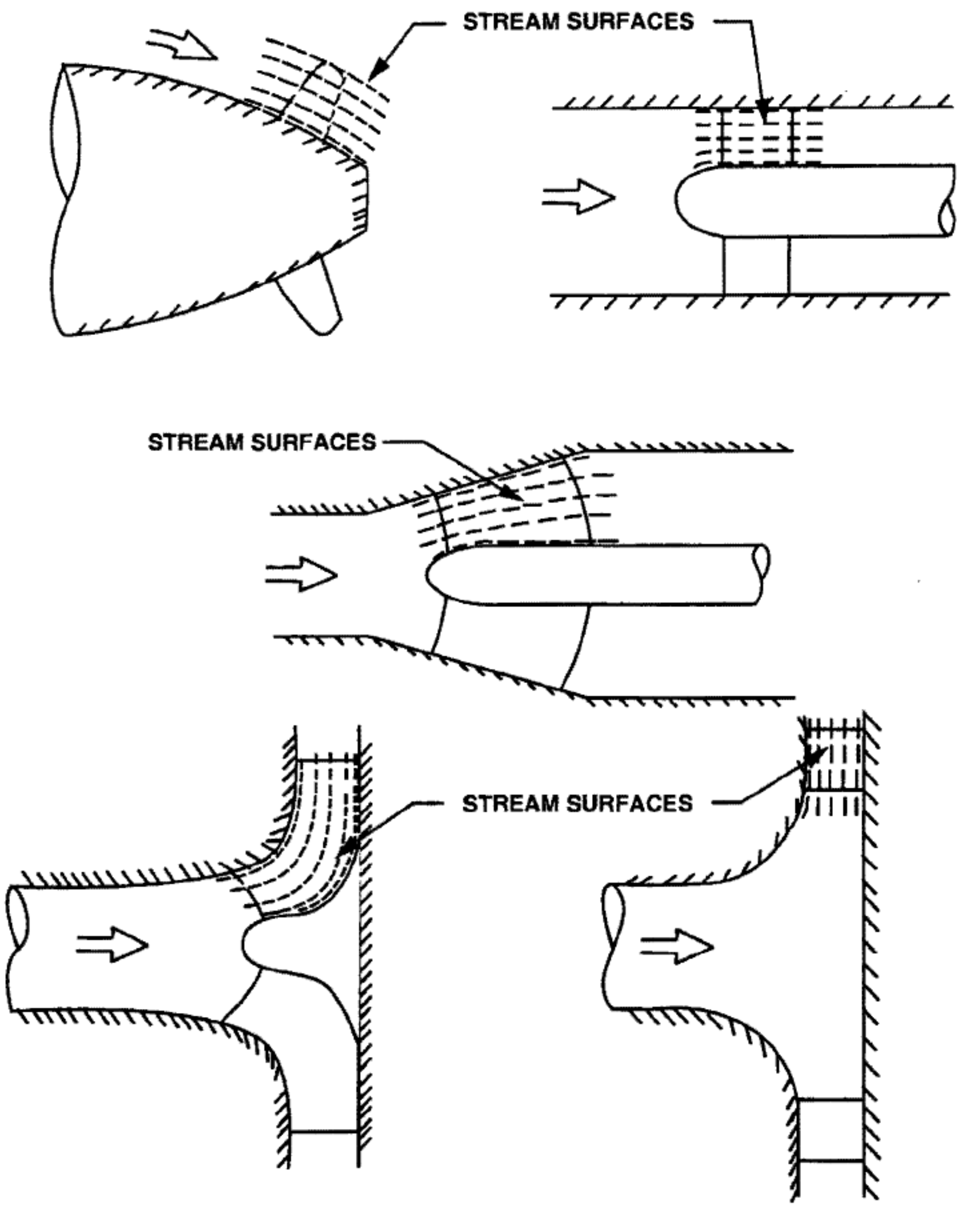

Figure 1. Various Types of Turbomachinery Blading Describable With the Use of Arbitrary Stream Surfaces

BLADE DESCRIPTION PARAMETERS

The blade section description parameters that are employed in the determination of the blade section surface coordinates are familiar ones; they are the blade section pitch angle, rake, skew, chord, camber, and thickness. Discussed below is the interpretation of these parameters in both the standard case of cylindrical stream surfaces and the generalized case of arbitrary stream surfaces.

Cylindrical Stream Surfaces

In the case of cylindrical stream surfaces, the blade description parameters are given as functions of the radius of the corresponding cylindrical streams surfaces. The parameters are defined as (reference 2):

ϕ Pitch Angle - The angle between the tangent to the blade section nose/tail pitch helix (directed from tail to nose) and the circumferential tangent to the cylindrical stream surface (directed clockwise looking upstream), in degrees.

x_m/D Rake - The axial displacement of the blade section midchord point from the blade reference line along the cylindrical stream surface, positive downstream, made dimensionless with respect to blade row diameter.

θ_m Skew - The circumferential angular displacement of the blade section midchord point from blade reference line, positive counterclockwise looking forward.

c/D Chord Length - The arclength along the blade section pitch line between the nose and tail of the blade section, dimensionless with respect to the blade row diameter.

f_{max}/c Maximum Blade Section Camber - Lying in the cylindrical stream surface defined normal to the blade pitch line, dimensionless with respect to the local blade chord.

t_{max}/c Maximum Blade Section Thickness - Lying in the cylindrical stream surface defined normal to the blade section camber line, dimensionless with respect to the local blade chord.

Here the pitch line is that helix on the cylindrical stream surface (and hence a geodesic) that passes through the leading and trailing edges of the blade section. The blade reference line, in this case, is that line beginning at the blade section midchord point at the hub, which is directed radially outward. Note that dimensionless camber and thickness distributions must also be given as functions of cylindrical stream surface radius.

The construction of the blade section then proceeds by displacing the blade section midchord point relative to the blade reference line both axially, through the rake, and circumferentially, through the skew. A pitch helix is then defined through this point, using the pitch angle at that radius, and the blade section chord is laid out along this helix symmetric with respect to the displaced midchord point. The blade section maximum camber is then used to dimensionalize the local camber distribution. This local camber distribution is then applied in the blade section

cylinder in a direction normal to the pitch helix and is parameterized along the pitch helix from the blade section leading edge to the blade section trailing edge. The blade section maximum thickness is then used to dimensionalize the local thickness distribution, which is then applied in the blade section cylinder in a direction normal to the blade section camber line and is parameterized along the blade section camber line from the blade section leading edge to the blade section trailing edge. Figure 2 illustrates the blade pitch angle, camber, and thickness on a cylindrical stream surfaces. Figures 3 and 4 show the definitions of the blade midchord skew and rake on cylindrical stream surfaces, respectively.

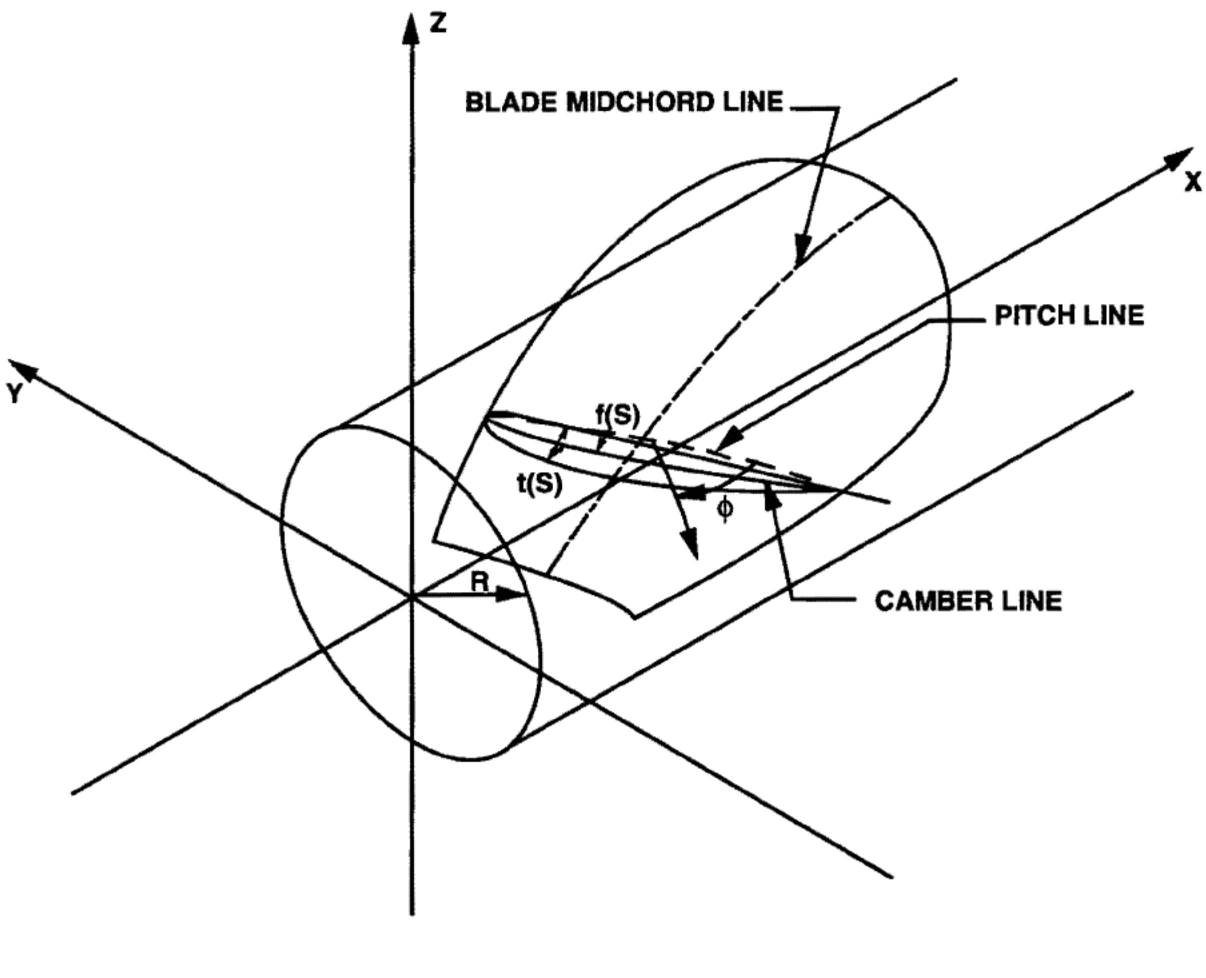

Figure 2. Blade Section Construction on Right Cylindrical Stream Surfaces

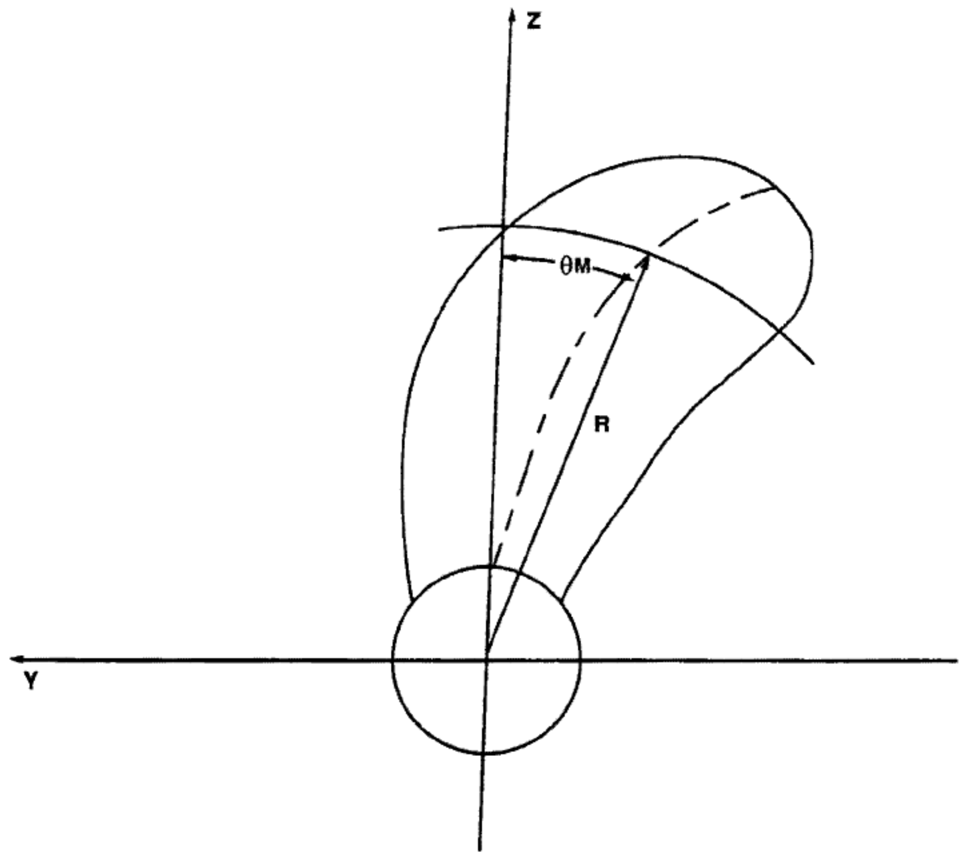

Figure 3. Blade Section Midchord Skew (Looking Downstream)

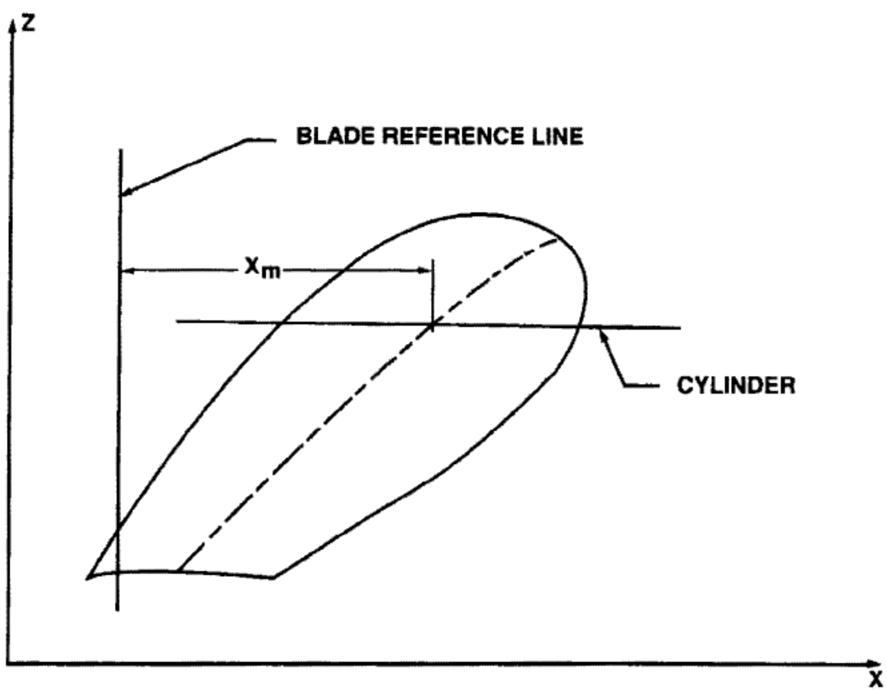

Figure 4. Blade Section Midchord Rake on Right Cylindrical Stream Surfaces (Looking to Starboard)

Arbitrary Stream Surfaces

In the case of arbitrary stream surfaces, the blade section description parameters are defined similarly. However, because these stream surfaces are not necessarily at constant radii, the section parameters must be defined as functions of the stream surface and the stream surfaces must parameterized to allow interpolation. To this end, the (x,r) stream surface space is mapped to the unit (s,t) square where s is the parameter along the stream surfaces and t is the parameter across stream surfaces. This mapping is illustrated in figure 5.

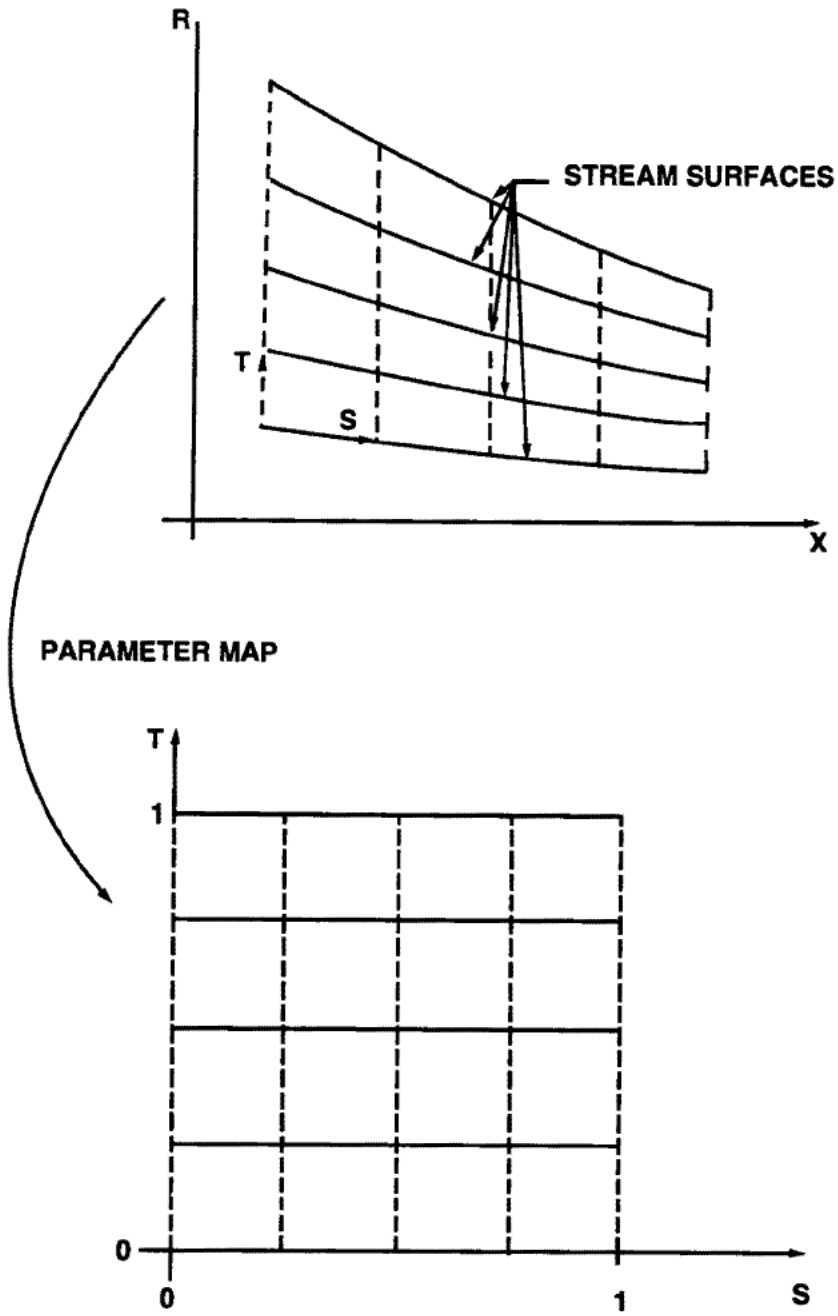

Figure 5. Stream Surface Parameterization for Arbitrary Axisymmetric Stream Surfaces

With this mapping in place, the blade section parameters are defined as functions of the parameter t as:

ϕ_m Midchord Pitch Angle - The angle between the tangent to the blade section pitch line at midchord (directed from tail to nose) with respect to the circumferential tangent to the stream surface (directed clockwise looking upstream), in degrees.

s_m/D Rake - The arclength displacement of the blade section midchord point from the blade reference line along the stream surface in the meridional direction, positive downstream, made dimensionless with respect to blade row diameter.

θ_m Skew - The circumferential angular displacement of the blade section midchord point from blade reference line, positive counterclockwise looking forward.

c/D Chord Length - The arclength along the blade section pitch line between the nose and tail of the blade section, dimensionless with respect to the blade row diameter.

f_{max}/c Maximum Blade Section Camber - Measured in the blade section stream surface normal to the blade pitch line, dimensionless with respect to the local blade chord.

t_{max}/c Maximum Blade Section Thickness - Measured in the blade section stream surface, normal to the blade section camber line, dimensionless with respect to the local blade chord.

Here the pitch line is that geodesic, lying on the stream surface that passes through the leading and trailing edges of the blade section. This generalization of the definition of the pitch line reduces to helices on cylindrical stream surfaces. In the general case, the blade reference line is that line beginning at the midchord point at the hub and progressing outward normal to the family of stream surfaces. Note that although the pitch angle of the pitch line is constant along the pitch line on cylindrical stream surfaces, this is not necessarily so on arbitrary stream surfaces. It is for this reason that the pitch angle on arbitrary stream surfaces is defined at the midchord of the pitch line.

The construction of the blade section proceeds by displacing the blade section midchord point along the local stream surface relative to the blade reference line both in the streamwise direction, through the rake, and circumferentially, through the skew. A pitch line is then defined through this point using the local geodesic curve, which possesses the local pitch angle at the midchord point. The blade section chord is laid out along this pitch line symmetrical with respect to the displaced midchord point. The blade section maximum camber is then used to dimensionalize the local camber distribution; this distribution is then applied in the local stream surface along a geodesic in a direction normal to the pitch line and parameterized along the pitch line. The blade section maximum thickness is then used to dimensionalize the local thickness distribution, which is then applied in the local stream surface along a geodesic in a direction normal to the blade section camber line and is parameterized along the camber line. Figure 6 presents an illustration of the blade pitch angle, camber and thickness on a arbitrary stream surfaces. Figure 7 shows the definitions of the blade midchord rake on arbitrary stream surfaces.

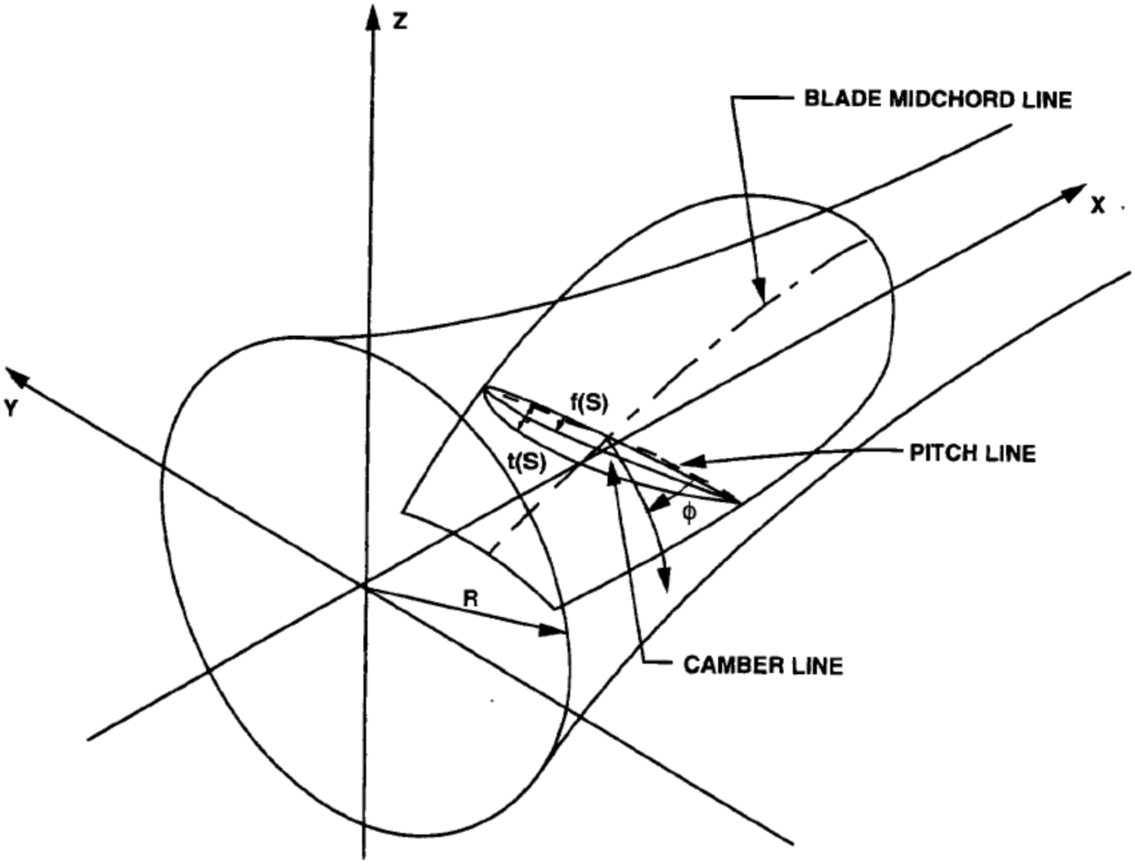

Figure 6. Blade Section Construction on Arbitrary Axisymmetric Stream Surfaces

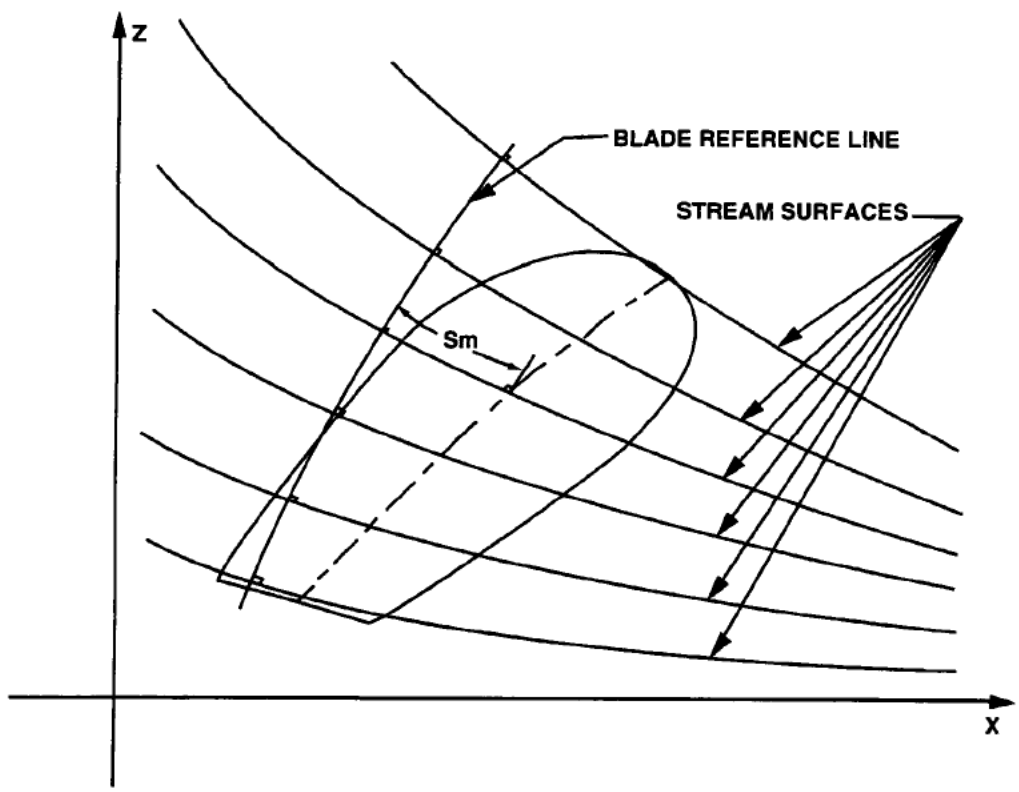

Figure 7. Blade Section Midchord Rake on Arbitrary Axisymmetric Stream Surfaces (Looking to Starboard)

The definition of midchord skew does not materially differ from that for cylindrical stream surfaces (see figure 3).

Note that a right-handed coordinate system is employed in both programs, PRPGEOM and PRMEXT. In this coordinate system, x is directed axially downstream, y is directed to starboard, and z is directed vertically upward.

THEORETICAL DEVELOPMENT

The concept of geodesic curves is central to this blade description scheme. These curves are simply defined as those curves at any point on a surface, which satisfy the equations

$$\frac{d\boldsymbol{T}}{ds} = \kappa \boldsymbol{N}, \qquad \frac{d\boldsymbol{x}}{ds} = \boldsymbol{T}, \tag{1}$$

where $\boldsymbol{x}$ is the locus of the curve, **T** is the tangent vector to the curve, s is the arclength along the curve, **N** is the vector normal to the surface and κ is the local curvature of the surface in the direction of the geodesic curve. Thus, for any sufficiently smooth surface, the specification of an initial direction at a point on that surface determines the geodesic curve uniquely.

The local curvature of the surface in the direction of the curve can be computed from a knowledge of the principal curvatures. Standard differential geometry texts (e.g., reference 3) prove that for any surface in $\mathbf{E}^3$, there exist two principal curvatures κ_1 and κ_2. Associated with these curvatures are two orthogonal principal directions that are denoted by the unit vectors $\mathbf{e}_1$ and $\mathbf{e}_2$. If the direction **u** in which the curvature is desired is given by

$$\boldsymbol{u} = cos(\theta)\boldsymbol{e}_1 + sin(\theta)\boldsymbol{e}_2, \tag{2}$$

then the curvature in that direction is simply

$$\kappa = \kappa_1\, cos^2(\theta) + \kappa_2\, sin^2(\theta)\cdot \tag{3}$$

For axisymmetric surfaces, the principal directions are just the meridians and the parallels of the surface. The principal curvatures are also straightforward. If the profile curve of the axisymmetric surface is defined as r=r(x) then the principal curvatures are given by

$$\kappa_1 = \frac{-d^2r/dx^2}{\left[1+(dr/dx)^2\right]^{3/2}}, \qquad \kappa_2 = \frac{1}{r\left[1+(dr/dx)^2\right]^{1/2}}, \tag{4}$$

where κ_1 is the principal curvature along the meridians and κ_2 is the principal curvature along the parallels.

Because the blade sections are defined on a distinct set of stream surfaces and the (x,y,z) blade surface coordinates must be able to be computed at arbitrary locations, it is necessary to parameterize the family of stream surfaces so that members of that family may be generated at any position between the blade root and tip. To do this, each of the input stream surfaces is parameterized along its length by an arclength parameter that is then normalized from zero to one. The family of input stream surfaces is then parameterized from zero to one with zero corresponding to the blade root stream surface and one corresponding to the blade tip stream surface. The mapping associated with this parameterization process is illustrated in figure 5.

The blade reference line is then defined as that line that begins on the blade root stream surface at the midchord of the blade root section and proceeds outward normal to the entire family of stream surfaces. This line lies wholly in the meridional plane, passing through the blade root section midchord point. The blade reference line is also illustrated in figure 7. The midchord line of the blade is defined relative to this blade reference line. Any point on the midchord line is located by displacing the intersection of the blade reference line with the relevant stream surface circumferentially through the skew angle and along a meridian of the stream surface the arclength distance specified by the rake.

The pitch line is defined as that line beginning at the section midchord point and proceeding along a geodesic on the stream surface both forward and aft for half of a chord length in each direction. The pitch angle is defined as that angle, lying in the stream surface, made by the forward-directed tangent to the pitch line with respect to a circumferential tangent to the stream surface (directed clockwise looking upstream).

The camber line is defined as the locus of points generated by selecting a point on the blade section pitch line and proceeding normal to the pitch line along a geodesic for an arclength equal to the local camber magnitude. The thickness is added on to the camber in a similar way. A point is selected on the camber line and the thickness is added by progressing along a geodesic normal to the camber line for an arclength equal to the local blade section semi-thickness.

The program PRMEXT begins by interpolating the blade surface coordinates onto one of the input stream surfaces to yield a blade section profile lying in that stream surface. It is assumed that the location of the trailing edge and the leading edge are known from the manner in which the blade surface coordinates are input. Determination of the pitch line begins by estimating the angle of the pitch line at the trailing edge, which causes the pitch line geodesic to pass through the leading edge point. Pitch line geodesic is then computed starting from the trailing edge with the estimated "shooting angle." The minimum separation of this line from the leading edge point is calculated and the shooting angle at the trailing edge is updated to reduce the minimum separation from the leading edge. This process is repeated until the pitch line passes through the leading edge to within the specified tolerance.

The pitch angle of the blade section is readily extracted from the pitch line geodesic. It is merely that angle made by the forward directed tangent to the pitch line at the blade section midchord with respect to the circumferential tangent to the stream surface (directed clockwise looking upstream).

Once the pitch line geodesic is known, the blade section midchord skew and rake are extracted. Both are determined relative to the blade reference line that is computed in the exact same manner in PRMEXT as it is in PRPGEOM; the midchord point of the pitch line is found. The angular circumferential displacement from the blade reference line equals the skew angle of the blade section, and the arclength displacement of the midchord point along a meridian of the stream surface equals the rake.

The camber line determination is somewhat more complicated. The initial guess for the camber line is obtained by taking the average of points on the pressure and suction sides of the blade and projecting them onto the stream surface under consideration. Geodesics are then generated normal to this estimated camber line and the distances to the intersections of these geodesics with the pressure and suction sides of the blade are determined. If these distances are not equal, the camber line point is adjusted to make them so. A new estimate of the camber line is thus produced and the process is iterated until convergence. This process also produces the camber and thickness distributions. The camber distribution is extracted as the displacement of the camber line along geodesics normal to the pitch line. The thickness distribution is extracted as the distance of either side of the blade section from the camber line measured along geodesics normal to the camber line.

PRPGEOM PROGRAM USAGE

This program is designed to construct blade surface coordinates from an input blade shape defined on arbitrary stream surfaces. Input to this program proceeds in two stages. First, the program reads an administrative file that includes the filename of the input data file and the number of spanwise and chordwise locations at which the blade surface coordinates are desired. The second stage of the input is the reading of the input data file, which actually defines the blade surface shape. This file contains the blade description parameters, the stream surface shapes, and the dimensionless blade camber and thickness distributions. Read statements are free-format wherever possible. The following sections describe the input format in detail.

INPUT FILE FORMAT

Administrative File Format

The quantities required in the "PRPGEOM.adm" file, and their formats, are shown below. An asterisk (*) in the column and format specifications indicates that the corresponding variable is read in using list-directed or free format.

COLUMN	VARIABLE	FORMAT	EXPLANATION
File Name record:			
1	FNAME	A80	Input data filename
Panel count record:			
*	MSPAN	*	Number of spanwise panels to be generated
*	NCHRD	*	Number of chordwise panels to be generated. Must be divisible by 4

Blade Input Data File Format

The blade input data file contains all the data necessary to generate the propulsor blade shape and to locate it on the body. The definitions of the parameters are contained in the "Blade Description Parameters" section of this report.

COLUMN	VARIABLE	FORMAT	EXPLANATION
Identifier record: (1=1,4)			
1-80	ID(1)	A80	Identifier for the blade geometry input file
Blade row number record:			
*	NBLDROW	*	Number of blade rows in the propulsor

COLUMN	VARIABLE	FORMAT	EXPLANATION
Blade number, location, and diameter record: (K=1,NBLDROW)			
*	NBLADES(K)	*	Number of blades in the Kth blade row
*	XPRP(K)	*	Axial location of the midchord at the hub for the Kth blade row
*	PRPDIA(K)	*	Diameter of Kth blade row
Input count record: (K=1,NBLDROW)			
*	NINBLD(K)	*	Number of input stream surfaces for the Kth blade row; must be greater than or equal to 4
*	NSTRM(K)	*	Number of input points defining each stream surface of the Kth blade row; must be greater than or equal to 4
*	NSECT(K)	*	Number of input stations defining each dimension-less camber and thickness distribution for the Kth blade row; must be greater than or equal to 4
Blade parameter input records: ((J=1,NINBLD(K)),K=1,NBLDROW)			
*	BS(J,K)	*	Dimensionless stream surface parameter for the Jth stream surface of the Kth blade row
*	BPTCH(J,K)	*	Pitch angle at the Jth stream surface of the Kth row (in degrees)

COLUMN	VARIABLE	FORMAT	EXPLANATION
Blade parameter input records: ((J=1,NINBLD(K)),K=1,NBLDROW) (Cont'd)			
*	BRAKE(J,K)	*	Rake of the blade at the Jth stream surface of the Kth blade row, dimensionless wrt* blade row diameter
*	BSKEW(J,K)	*	Skew angle of the blade at the Jth stream surface of the Kth blade row (in degrees)
*	BCHRD(J,K)	*	Chord length of the blade at the Jth stream surface of the Kth blade row, dimensionless wrt blade row diameter
*	BCMBR(J,K)	*	Maximum camber of the blade at the Jth stream surface of the Kth blade row, dimensionless wrt local blade chord
*	BTHCK(J,K)	*	Maximum thickness of the blade at the Jth stream surface of the Kth blade row, dimensionless wrt local blade chord
Stream surface input records: ((I=1,NSTRM(K),J=1,NINBLD(K)),K=1,NBLDROW)			
*	XSTRM(I,J,K)	*	Axial stream surface input array for the Jth stream surface of the Kth blade row, dimensionless wrt blade row diameter
*	RSTRM(I,J,K)	*	Radial stream surface input array for the Jth stream surface of the Kth blade row, dimensionless wrt blade row diameter

*wrt = with respect to.

COLUMN	VARIABLE	FORMAT	EXPLANATION
Camber and thickness distribution input records: ((I=1,NSECT(K),J=1,NINBLD(K)),K=1,NBLDROW)			
*	SRADLE(J,K)	*	Leading edge radius for the thickness distribution for the Jth stream surface of the Kth blade row, dimensionless wrt* local maximum thickness
*	SSECT(I,J,K)	*	Arclength variable along the camber or thickness distribution for the Jth stream surface of the Kth blade row, dimensionless wrt local chord
*	STHCK(I,J,K)	*	Thickness distribution for the Jth stream surface of the Kth blade row, dimensionless wrt local maximum thickness
*	SCMBR(I,J,K)	*	Camber distribution for the Jth stream surface of the Kth blade row, dimensionless wrt local maximum camber

*wrt = with respect to.

All input arrays are assumed to define differentiable functions. The definition of a function employed herein is a computational one wherein a function is assumed to be defined by the combination of a set of input arrays and a corresponding interpolation rule. The interpolation rules employed in this program are blended third-order Lagrangian interpolators (blended quadratic interpolation).

CAVEATS

The program PRPGEOM encounters problems when run for certain degenerate or extreme cases. Fortunately, these cases are usually either out of the range of typical propulsor design or may be overcome through slight redefinition of the blade shape. These issues are as follows:

- It is necessary to redefine the blade shape to eliminate any sections with zero chord lengths. The program assumes that the chords at all sections are nonzero and will crash if a chord length of zero is encountered.

- The IBM version of PRPGEOM can only handle one blade row at a time.
- The stream surfaces on which the blade sections are defined should be defined in such a manner as to allow easy parameterization of the stream surfaces. Peculiar results will be obtained for choices of stream surfaces that do not permit smooth parameterization.

INPUT FILE EXAMPLES

An example of an administrative file designed to run PRPGEOM for the blade input file TESTBLD.DAT with 10 spanwise panels and 20 chordwise panels is given below.

```
TESTBLD.DAT
10        20
```

Examples of blade input data files are given below. The first is for a case wherein the stream surfaces are given as cylinders.

```
TESTBLD.DAT
DESIGN J=XXXX
DUMMY FILE TO TEST NEW BLADE DESCRIPTION PROGRAM
NACA 65 (PARABOLIC) MEANLINES, NACA 00XX THICKNESS SECTIONS

 1
 7        0.00     1.00
 5        5        19

 0.00     60.82    0.00000    0.000    0.2070    0.0490    0.04140
 0.25     45.71    0.04766   14.557    0.2722    0.0367    0.03607
 0.50     34.78    0.10000   29.647    0.2684    0.0300    0.02362
 0.75     24.40    0.13143   41.595    0.1815    0.0281    0.01071
 1.00     12.94    0.11952   47.376    0.0001    0.0000    0.00001

-1.00    -0.50     0.00      0.50      1.00
 0.20     0.20     0.20      0.20      0.20
-1.00    -0.50     0.00      0.50      1.00
 0.40     0.40     0.40      0.40      0.40
-1.00    -0.50     0.00      0.50      1.00
 0.60     0.60     0.60      0.60      0.60
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 1.00     1.00     1.00      1.00      1.00
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4.3965						
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0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2413	0.1343	0.0210		
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0.8400	0.6400	0.3600	0.1900	0.0000		
4.3965						
0.0000	0.0050	0.0125	0.0250	0.0500	0.0750	0.1000
0.1500	0.2000	0.2500	0.3000	0.4000	0.5000	0.6000
0.7000	0.8000	0.9000	0.9500	1.0000		
0.0000	0.2097	0.3155	0.4354	0.5922	0.6997	0.7801
0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2413	0.1343	0.0210		
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0.5100	0.6400	0.7500	0.8400	0.9600	1.0000	0.9600
0.8400	0.6400	0.3600	0.1900	0.0000		
4.3965						
0.0000	0.0050	0.0125	0.0250	0.0500	0.0750	0.1000
0.1500	0.2000	0.2500	0.3000	0.4000	0.5000	0.6000
0.7000	0.8000	0.9000	0.9500	1.0000		
0.0000	0.2097	0.3155	0.4354	0.5922	0.6997	0.7801
0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2413	0.1343	0.0210		
0.0000	0.0199	0.0493	0.0975	0.1900	0.2775	0.3600
0.5100	0.6400	0.7500	0.8400	0.9600	1.0000	0.9600
0.8400	0.6400	0.3600	0.1900	0.0000		
4.3965						
0.0000	0.0050	0.0125	0.0250	0.0500	0.0750	0.1000
0.1500	0.2000	0.2500	0.3000	0.4000	0.5000	0.6000
0.7000	0.8000	0.9000	0.9500	1.0000		
0.0000	0.2097	0.3155	0.4354	0.5922	0.6997	0.7801
0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2413	0.1343	0.0210		
0.0000	0.0199	0.0493	0.0975	0.1900	0.2775	0.3600
0.5100	0.6400	0.7500	0.8400	0.9600	1.0000	0.9600
0.8400	0.6400	0.3600	0.1900	0.0000		
4.3965						
0.0000	0.0050	0.0125	0.0250	0.0500	0.0750	0.1000
0.1500	0.2000	0.2500	0.3000	0.4000	0.5000	0.6000
0.7000	0.8000	0.9000	0.9500	1.0000		
0.0000	0.2097	0.3155	0.4354	0.5922	0.6997	0.7801
0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2413	0.1343	0.0210		

```
 0.0000    0.0199    0.0493    0.0975    0.1900    0.2775    0.3600
 0.5100    0.6400    0.7500    0.8400    0.9600    1.0000    0.9600
 0.8400    0.6400    0.3600    0.1900    0.0000

12345678  12345678  12345678  12345678  12345678  12345678  12345678
123456789012345678901234567890123456789012345678901234567890123456789012
```

The following blade input data file is for a case where the input stream surfaces are given as parallel conical surfaces.

```
TESTBLD.DAT
DESIGN J=XXXX
DUMMY FILE TO TEST NEW BLADE DESCRIPTION PROGRAM
NACA 65 (PARABOLIC) MEANLINES, NACA 00XX THICKNESS SECTIONS

   1
   7        0.00      1.00
   5        5         19
   0.00     60.82     0.00000   0.000     0.2070    0.0490    0.04140
   0.25     45.71     0.04766   14.557    0.2722    0.0367    0.03607
   0.50     34.78     0.10000   29.647    0.2684    0.0300    0.02362
   0.75     24.40     0.13143   41.595    0.1815    0.0281    0.01071
   1.00     12.94     0.11952   47.376    0.0001    0.0000    0.00001

  -1.00    -0.50      0.00      0.50      1.00
   0.20     0.20      0.20      0.20      0.20
  -1-00    -0.50      0.00      0.50      1.00
   0.45     0.425     0.40      0.375     0.35
  -1.00    -0.50      0.00      0.50      1.00
   0.70     0.65      0.60      0.55      0.50
  -1.00    -0.50      0.00      0.50      1.00
   0.95     0.875     0.80      0.725     0.65
  -1.00    -0.50      0.00      0.50      1.00
   1.20     1.10      1.00      0.90      0.80

   4.3965
   0.0000   0.0050    0.0125    0.0250    0.0500    0.0750    0.1000
   0.1500   0.2000    0.2500    0.3000    0.4000    0.5000    0.6000
   0.7000   0.8000    0.9000    0.9500    1.0000
   0.0000   0.2097    0.3155    0.4354    0.5922    0.6997    0.7801
   0.8906   0.9560    0.9900    1.0000    0.9670    0.8820    0.7603
   0.6104   0.4372    0.2413    0.1343    0.0210
   0.0000   0.0199    0.0493    0.0975    0.1900    0.2775    0.3600
   0.5100   0.6400    0.7500    0.8400    0.9600    1.0000    0.9600
   0.8400   0.6400    0.3600    0.1900    0.0000
   4.3965
   0.0000   0.0050    0.0125    0.0250    0.0500    0.0750    0.1000
   0.1500   0.2000    0.2500    0.3000    0.4000    0.5000    0.6000
```

```
0.7000   0.8000   0.9000   0.9500   1.0000
0.0000   0.2097   0.3155   0.4354   0.5922   0.6997   0.7801
0.8906   0.9560   0.9900   1.0000   0.9670   0.8820   0.7603
0.6104   0.4372   0.2413   0.1343   0.0210
0.0000   0.0199   0.0493   0.0975   0.1900   0.2775   0.3600
0.5100   0.6400   0.7500   0.8400   0.9600   1.0000   0.9600
0.8400   0.6400   0.3600   0.1900   0.0000
4.3965
0.0000   0.0050   0.0125   0.0250   0.0500   0.0750   0.1000
0.1500   0.2000   0.2500   0.3000   0.4000   0.5000   0.6000
0.7000   0.8000   0.9000   0.9500,  1.0000
0.0000   0.2097   0.3155   0.4354   0.5922   0.6997   0.7801
0.8906   0.9560   0.9900   1.0000   0.9670   0.8820   0.7603
0.6104   0.4372   0.2413   0.1343   0.0210
0.0000   0.0199   0.0493   0.0975   0.1900   0.2775   0.3600
0.5100   0.6400   0.7500   0.8400   0.9600   1.0000   0.9600
0.8400   0.6400   0.3600   0.1900   0.0000
4.3965
0.0000   0.0050   0.0125   0.0250   0.0500   0.0750   0.1000
0.1500   0.2000   0.2500   0.3000   0.4000   0.5000   0.6000
0.7000   0.8000   0.9000   0.9500   1.0000
0.0000   0.2097   0.3155   0.4354   0.5922   0.6997   0.7801
0.8906   0.9560   0.9900   1.0000   0.9670   0.8820   0.7603
0.6104   0.4372   0.2413   0.1343   0.0210
0.0000   0.0199   0.0493   0.0975   0.1900   0.2775   0.3600
0.5100   0.6400   0.7500   0.8400   0.9600   1.0000   0.9600
0.8400   0.6400   0.3600   0.1900   0.0000
4.3965
0.0000   0.0050   0.0125   0.0250   0.0500   0.0750   0.1000
0.1500   0.2000   0.2500   0.3000   0.4000   0.5000   0.6000
0.7000   0.8000   0.9000   0.9500   1.0000
0.0000   0.2097   0.3155   0.4354   0.5922   0.6997   0.7801
0.8906   0.9560   0.9900   1.0000   0.9670   0.8820   0.7603
0.6104   0.4372   0.2413   0.1343   0.0210
0.0000   0.0199   0.0493   0.0975   0.1900   0.2775   0.3600
0.5100   0.6400   0.7500   0.8400   0.9600   1.0000   0.9600
0.8400   0.6400   0.3600   0.1900   0.0000

12345678 12345678 12345678 12345678 12345678 12345678 12345678
12345678901234567890123456789012345678901234567890123456789012
```

The following blade input data file is for a case where the input stream surfaces are given as a series of cones of increasing half angle.

```
TESTBLD.DAT
DESIGN J=XXXX
DUMMY FILE TO TEST NEW BLADE DESCRIPTION PROGRAM
NACA 65 (PARABOLIC) MEANLINES, NACA 00XX THICKNESS SECTIONS
```

1						
7	0.00	1.00				
5	5	19				
0.00	60.82	0.00000	0.000	0.2070	0.0490	0.04140
0.25	45.71	0.04766	14.557	0.2722	0.0367	0.03607
0.50	34.78	0.10000	29.647	0.2684	0.0300	0.02362
0.75	24.40	0.13143	41.595	0.1815	0.0281	0.01071
1.00	12.94	0.11952	47.376	0.0946	0.0262	0.00426
-1.00	-0.50	0.00	0.50	1.00		
0.20	0.20	0.20	0.20	0.20		
-1.00	-0.50	0.00	0.50	1.00		
0.45	0.425	0.40	0.375	0.35		
-1.00	-0.50	0.00	0.50	1.00		
0.70	0.65	0.60	0.55	0.50		
-1.00	-0.50	0.00	0.50	1.00		
0.95	0.875	0.80	0.725	0.65		
-1.00	-0.50	0.00	0.50	1.00		
1.20	1.10	1.00	0.90	0.80		
4.3965						
0.0000	0.0050	0.0125	0.0250	0.0500	0.0750	0.1000
0.1500	0.2000	0.2500	0.3000	0.4000	0.5000	0.6000
0.7000	0.8000	0.9000	0.9500	1.0000		
0.0000	0.2097	0.3155	0.4354	0.5922	0.6997	0.7801
0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2361	0.1225	0.0000		
0.0000	0.0199	0.0493	0.0975	0.1900	0.2775	0.3600
0.5100	0.6400	0.7500	0.8400	0.9600	1.0000	0.9600
0.8400	0.6400	0.3600	0.1900	0.0000		
4.3965						
0.0000	0.0050	0.0125	0.0250	0.0500	0.0750	0.1000
0.1500	0.2000	0.2500	0.3000	0.4000	0.5000	0.6000
0.7000	0.8000	0.9000	0.9500	1.0000		
0.0000	0.2097	0.3155	0.4354	0.5922	0.6997	0.7801
0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2361	0.1225	0.0000		
0.0000	0.0199	0.0493	0.0975	0.1900	0.2775	0.3600
0.5100	0.6400	0.7500	0.8400	0.9600	1.0000	0.9600
0.8400	0.6400	0.3600	0.1900	0.0000		
4.3965						
0.0000	0.0050	0.0125	0.0250	0.0500	0.0750	0.1000
0.1500	0.2000	0.2500	0.3000	0.4000	0.5000	0.6000
0.7000	0.8000	0.9000	0.9500	1.0000		
0.0000	0.2097	0.3155	0.4354	0.5922	0.6997	0.7801
0.8906	0.9560	0.9900	1.0000	0.9670	0.8820	0.7603
0.6104	0.4372	0.2361	0.1225	0.0000		
0.0000	0.0199	0.0493	0.0975	0.1900	0.2775	0.3600

```
0.5100    0.6400    0.7500    0.8400    0.9600    1.0000    0.9600
0.8400    0.6400    0.3600    0.1900    0.0000
4.3965
0.0000    0.0050    0.0125    0.0250    0.0500    0.0750    0.1000
0.1500    0.2000    0.2500    0.3000    0.4000    0.5000    0.6000
0.7000    0.8000    0.9000    0.9500    1.0000
0.0000    0.2097    0.3155    0.4354    0.5922    0.6997    0.7801
0.8906    0.9560    0.9900    1.0000    0.9670    0.8820    0.7603
0.6104    0.4372    0.2361    0.1225    0.0000
0.0000    0.0199    0.0493    0.0975    0.1900    0.2775    0.3600
0.5100    0.6400    0.7500    0.8400    0.9600    1.0000    0.9600
0.8400    0.6400    0.3600    0.1900    0.0000
4.3965
0.0000    0.0050    0.0125    0.0250    0.0500    0.0750    0.1000
0.1500    0.2000    0.2500    0.3000    0.4000    0.5000    0.6000
0.7000    0.8000    0.9000    0.9500    1.0000
0.0000    0.2097    0.3155    0.4354    0.5922    0.6997    0.7801
0.8906    0.9560    0.9900    1.0000    0.9670    0.8820    0.7603
0.6104    0.4372    0.2361    0.1225    0.0000
0.0000    0.0199    0.0493    0.0975    0.1900    0.2775    0.3600
0.5100    0.6400    0.7500    0.8400    0.9600    1.0000    0.9600
0.8400    0.6400    0.3600    0.1900    0.0000

12345678  12345678  12345678  12345678  12345678  12345678  12345678
12345678901234567890123456789012345678901234567890123456789012
```

PRMEXT PROGRAM USAGE

This program is designed to extract the blade description parameters required by the PRPGEOM program for the construction of the blade surface coordinates. Input data for this program consist of two files: (1) an input file, a blade geometry file, that contains the (x,y,z) coordinates of the pressure and suction sides of the blade, and (2) a second input file that provides a description of the stream surfaces on which the parameterized description is desired. Both files are requested interactively. The blade geometry coordinate file may be read in a variety of formats, which the user can select during the input process. The format described below is referred to as the PRPGEOM format. Once again, read statements are format-free wherever possible. A detailed description of the input format appears in the following sections.

INPUT FILE FORMAT

Blade Input Data File Format

The quantities required in the blade geometry input file and their formats are shown below. An asterisk (*) in the column and format specifications indicates that the corresponding variable is read in using list-directed or free format.

COLUMN	VARIABLE	FORMAT	EXPLANATION
Identifier record:			
1-80	ID(I)	A80	Identifier for the blade geometry input file
Spanwise and chordwise count record:			
*	MBLD	*	Number of spanwise points
*	NBLD	*	Number of chordwise points per side

(Note: NBLD must be odd so that there exists a data point at the leading edge.)

Blade geometry coordinate records: (I=1,MBLD) Suction side coordinate records: (J=NBLD,1,-1)			
*	XSS(I,J)	*	Suction side x coordinate value
*	YSS(I,J)	*	Suction side y coordinate value
*	ZSS(I,J)	*	Suction side z coordinate value

COLUMN	VARIABLE	FORMAT	EXPLANATION
Pressure side coordinate records: (J=2,NBLD)			
*	XPS(I,J)	*	Pressure side x coordinate value
*	YPS(I,J)	*	Pressure side y coordinate value
*	ZPS(I,J)	*	Pressure side z coordinate value

(Assumes that XPS(I,1)=XSS(I,1), YPS(I,1)=YSS(I,1), ZPS(I,1)=XSS(I,1) for all I).

Stream Surface Input Data File Format

The stream surface input file contains the data defining the shape of the stream surfaces on which the generalized, parameterized description of the blade is desired. The definitions of these quantities are given in the section of the report on the formulation of the geometric description.

COLUMN	VARIABLE	FORMAT	EXPLANATION
Identifier record: (I=1,4)			
1-80	IDSTRM(I)	A80	Identifier for the blade geometry input file
Input count record:			
*	NINBLD	*	Number of input stream surfaces; must be greater than or equal to 4
*	NSTRM	*	Number of input points defining each stream surface; must be greater than or equal to 4
Stream surface input records: (I=1,NSTRM,J=1,NINBLD)			
*	XSTRM(I,J)	*	Axial stream surface input array for the Jth stream surface dimensionless wrt blade row diameter
*	RSTRM(I,J)	*	Radial stream surface input array for the Jth stream surface, dimensionless wrt blade row diameter

All input arrays are assumed to define differentiable functions. The definition of a function employed herein is a computational one wherein a function is assumed to be defined by the combination of a set of input arrays and a corresponding interpolation rule. The interpolation rules employed in this program are blended third-order Lagrangian interpolators (blended quadratic interpolation).

CAVEATS

The program PRMEXT encounters problems when run for certain degenerate or extreme cases. Fortunately, these cases are usually either out of the range of typical propulsor design or may be overcome through slight redefinition of the blade shape. These issues are presented below.

- Small c/D values (on the order of 0.0001 or smaller) lower the accuracy of the calculation of pitch angles. Chord lengths of zero will cause the program to crash or behave strangely.

- High thickness ratios (t/c on the order of 0.20) and a low number of defining points per chordwise section (less than roughly 20) will cause PRMEXT to terminate prematurely.

- Small c/D and t/c ratios (less than 0.001 approximately) may result in poorly shaped camber and thickness distributions.

- PRMEXT fits a circle through the leading edge and the adjacent points on the pressure and suction sides of a given section to determine the leading edge radius. Data should be closely spaced near the leading edge for an accurate calculation. This is especially true for thin sections (t/c less than 0.05 roughly).

- Thick sections require more iterations in the routine that determines the section meanline (subroutine CMBRLIN).

- Unpredictable results occur in PRMEXT when the hub or tip (or both) stream surfaces do not intersect the blade geometry input data.

The output file generated by the program PRMEXT currently contains two additional columns following the maximum blade section thickness values. These two columns describe the sweep angles of the leading and trailing edges of the blade sections and are for informational purposes only; they may be retained or deleted as seen fit by the user.

INPUT FILE EXAMPLES

An example of a blade input data file is given below. The first is for a case wherein the stream surfaces are given as cones.

```
TESTBLD.DAT
DESIGN J=XXXX
DUMMY FILE TO TEST NEW BLADE DESCRIPTION PROGRAM
NACA 65 (PARABOLIC) MEANLINES, NACA 00XX THICKNESS SECTIONS

    6                21
    9.03648E-02      -4.99282E-02      1.93668E-01
    8.55542E-02      -4.81091E-02      1.94128E-01
    7.17356E-02      -4.26369E-02      1.95402E-01
    5.06214E-02      -3.35159E-02      1.97172E-01
```

2.47198E-02	-2.09280E-02	1.98002E-01
-3.10260E-03	-5.55567E-03	1.99923E-01
-3.01062E-02	1.11603E-02	1.99688E-01
-5.39430E-02	2.71297E-02	1.98151E-01
-7.27767E-02	4.00842E-02	1.95942E-01
-8.52225E-02	4.81028E-02	1.94129E-01
-9.03651E-02	4.99282E-02	1.93668E-01
-8.76069E-02	4.53143E-02	1.94799E-01
-7.68531E-02	3.49904E-02	1.96915E-01
-5.87596E-02	2.04793E-02	1.98949E-01
-3.46900E-02	4.00153E-03	1.99960E-01
-6.78474E-03	-1.21495E-02	1.99631E-01
2.21812E-02	-2.61652E-02	1.98281E-01
4.91368E-02	-3.70255E-02	1.96543E-01
7.10616E-02	-4.44281E-02	1.95003E-01
8.53852E-02	-4.85958E-02	1.94006E-01
9.03648E-02	-4.99282E-02	1.93668E-01
1.39365E-01	-1.54300E-01	3.19075E-01
1.34082E-01	-1.50890E-01	3.20935E-01
1.18912E-01	-1.40768E-01	3.26163E-01
9.57538E-02	-1.24311E-01	3.33772E-01
6.74052E-02	-1.02334E-01	3.42336E-01
3.70404E-02	-7.63845E-02	3.50287E-01
7.64024E-03	-4.89223E-02	3.56352E-01
-1.82912E-02	-2.31145E-02	3.59990E-01
-3.88222E-02	-2.24780E-03	3.61546E-01
-5.25033E-02	1.08983E-02	3.61936E-01
-5.83869E-02	1.44891E-02	3.62046E-01
-5.57955E-02	8.08491E-03	3.62142E-01
-4.45454E-02	-7.35486E-03	3.61707E-01
-2.52500E-02	-2.97301E-02	3.59784E-01
7.41839E-04	-5.59900E-02	3.55589E-01
3.11985E-02	-8.28516E-02	3.49054E-01
6.31164E-02	-1.07440E-01	3.40947E-01
9.30696E-02	-1.27714E-01	3.32600E-01
1.17613E-01	-1.42495E-01	3.25469E-01
1.33741E-01	-1.51357E-01	3.20730E-01
1.39365E-01	-1.54300E-01	3.19075E-01
1.79312E-01	-2.98081E-01	4.08454E-01
1.74626E-01	-2.94215E-01	4.11708E-01
1.61172E-01	-2.82748E-01	4.20964E-01
1.40639E-01	-2.64132E-01	4.34810E-01
1.15522E-01	-2.39346E-01	4.51207E-01
8.86497E-02	-2.10167E-01	4.67872E-01
6.26718E-02	-1.79308E-01	4.82763E-01
3.97975E-02	-1.50203E-01	4.94508E-01
2.17208E-02	-1.26460E-01	5.02597E-01
9.69303E-03	-1.11209E-01	5.07175E-01

4.51386E-03	-1.06560E-01	5.08596E-01
6.75297E-03	-1.13119E-01	5.06994E-01
1.65697E-02	-1.29908E-01	5.02142E-01
3.34532E-02	-1.54634E-01	4.93672E-01
5.62716E-02	-1.84002E-01	4.81541E-01
8.31131E-02	-2.14428E-01	4.66422E-01
1.11361E-01	-2.42686E-01	4.49797E-01
1.37973E-01	-2.66344E-01	4.33709E-01
1.59856E-01	-2.83865E-01	4.20338E-01
1.74276E-01	-2.94517E-01	4.11527E-01
1.79312E-01	-2.98081E-01	4.08454E-01
2.03491E-01	-4.55061E-01	4.71918E-01
2.00152E-01	-4.51833E-01	4.75562E-01
1.90585E-01	-4.42266E-01	4.86025E-01
1.76039E-01	-4.26769E-01	5.01981E-01
1.58344E-01	-4.06194E-01	5.21465E-01
1.39549E-01	-3.82025E-01	5.42184E-01
1.21545E-01	-3.56461E-01	5.61883E-01
1.05863E-01	-3.32267E-01	5.78691E-01
9.36258E-02	-3.12383E-01	5.91324E-01
8.56038E-02	-2.99420E-01	5.99068E-01
8.22587E-02	-2.95176E-01	6.01618E-01
8.39084E-02	-3.00235E-01	5.98888E-01
9.06438E-02	-3.13853E-01	5.90950E-01
1.02168E-01	-3.34157E-01	5.78114E-01
1.17786E-01	-3.58466E-01	5.61141E-01
1.36266E-01	-3.83850E-01	5.41376E-01
1.55851E-01	-4.07631E-01	5.20723E-01
1.74426E-01	-4.27725E-01	5.01421E-01
1.89782E-01	-4.42751E-01	4.85713E-01
1.99938E-01	-4.51964E-01	4.75473E-01
2.03491E-01	-4.55061E-01	4.71918E-01
2.11139E-01	-6.05166E-01	5.32692E-01
2.09334E-01	-6.02996E-01	5.35583E-01
2.04189E-01	-5.96593E-01	5.43928E-01
1.96448E-01	-5.86309E-01	5.56799E-01
1.87174E-01	-5.72801E-01	5.72786E-01
1.77518E-01	-5.57110E-01	5.90185E-01
1.68492E-01	-5.40667E-01	6.07219E-01
1.60849E-01	-5.25199E-01	6.22248E-01
1.55061E-01	-5.12510E-01	6.33931E-01
1.51383E-01	-5.04199E-01	6.41310E-01
1.49928E-01	-5.01370E-01	6.43819E-01
1.50784E-01	-5.04404E-01	6.41271E-01
1.54006E-01	-5.12882E-01	6.33847E-01
1.59537E-01	-5.25683E-01	6.22114E-01
1.67151E-01	-5.41189E-01	6.07042E-01
1.76340E-01	-5.57593E-01	5.89988E-01

1.86274E-01	-5.73188E-01	5.72602E-01
1.95863E-01	-5.86571E-01	5.56659E-01
2.03896E-01	-5.96728E-01	5.43850E-01
2.09255E-01	-6.03033E-01	5.35560E-01
2.11139E-01	-6.05166E-01	5.32692E-01
2.05084E-01	-7.36012E-01	6.14740E-01
2.04381E-01	-7.34699E-01	6.16528E-01
2.02397E-01	-7.30848E-01	6.21700E-01
1.99476E-01	-7.24734E-01	6.29709E-01
1.96087E-01	-7.16825E-01	6.39715E-01
1.92712E-01	-7.07791E-01	6.50694E-01
1.89733E-01	-6.98476E-01	6.61551E-01
1.87372E-01	-6.89832E-01	6.71236E-01
1.85703E-01	-6.82813E-01	6.78849E-01
1.84700E-01	-6.78237E-01	6.83703E-01
1.84313E-01	-6.76661E-01	6.85372E-01
1.84531E-01	-6.78278E-01	6.83710E-01
1.85403E-01	-6.82888E-01	6.78859E-01
1.86997E-01	-6.89931E-01	6.71242E-01
1.89348E-01	-6.98585E-01	6.61547E-01
1.92373E-01	-7.07895E-01	6.50682E-01
1.95826E-01	-7.16910E-01	6.39698E-01
1.99305E-01	-7.24793E-01	6.29693E-01
2.02312E-01	-7.30879E-01	6.21691E-01
2.04358E-01	-7.34707E-01	6.16525E-01
2.05084E-01	-7.36012E-01	6.14740E-01

An example of a stream surface input data file is given below.

TESTBLD.DAT
DESIGN J=XXXX

DUMMY FILE TO TEST NEW BLADE DESCRIPTION PROGRAM
NACA 65 (PARABOLIC) MEANLINES, NACA 00XX THICKNESS SECTIONS
5
5

-1.00	-0.50	0.00	0.50	1.00
0.20	0.20	0.20	0.20	0.20
-1.00	-0.50	0.00	0.50	1.00
0.45	0.425	0.40	0.375	0.35
-1.00	-0.50	0.00	0.50	1.00
0.70	0.65	0.60	0.55	0.50

-1.00	-0.50	0.00	0.50	1.00
0.95	0.875	0.80	0.725	0.65

-1.00	-0.50	0.00	0.50	1.00
1.20	1.10	1.00	0.90	0.80

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3. B. O'Neill, *Elementary Differential Geometry,* Academic Press, New York (1966).

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